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Search for high-mass dilepton resonances using 139 fb^{-1} of pp collision data collected at $\sqrt{s} = 13$ TeV with the ATLAS detector

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ABSTRACT

A search for high-mass dielectron and dimuon resonances in the mass range of 250 GeV to 6 TeV is presented. The data were recorded by the ATLAS experiment in proton–proton collisions at a centre-of-mass energy of $\sqrt{s} = 13$ TeV during Run 2 of the Large Hadron Collider and correspond to an integrated luminosity of 139 fb^{-1}. A functional form is fitted to the dilepton invariant-mass distribution to model the contribution from background processes, and a generic signal shape is used to determine the significance of observed deviations from this background estimate. No significant deviation is observed and upper limits are placed at the 95% confidence level on the fiducial cross-section times branching ratio for various resonance width hypotheses. The derived limits are shown to be applicable to spin-0, spin-1 and spin-2 signal hypotheses. For a set of benchmark models, the limits are converted into lower limits on the resonance mass and reach 4.5 TeV for the E_6-motivated Z'_ψ boson. Also presented are limits on Heavy Vector Triplet model couplings.

1. Introduction

Searches in the dilepton (dielectron and dimuon) final state have a long and illustrious history with the discovery of the J/ψ meson in 1974 [1,2] and Υ meson in 1977 [3] as well as the Z boson in 1983 [4,5]. As these were key steps which led to the establishment of the Standard Model (SM) of particle physics, the study of the same final state could help to pave the way to a better understanding of the physics processes beyond it.

Various models predict resonances which decay into dileptons and can be categorised according to their spin. A new high-mass spin-0 resonance, H, introduced as part of an extended scalar sector in some models, such as the Minimal Supersymmetric SM (MSSM) [6], has higher decay rate into a pair of muons rather than electrons. The majority of searches for new neutral high-mass resonances have focused on a new spin-1 vector boson, generally referred to as Z', that appears in models with extended gauge symmetries. Typical benchmark models include the Sequential Standard Model Z'_{SSM} boson [7], which has the same fermion couplings as the SM Z boson, a Z'_χ and a Z'_ψ boson of an E_6-motivated Grand Unification model [8], or a Z'_{HVT} boson of the Heavy Vector Triplet model [9]. In the first two models, the Z' boson is a singlet, associated with a new U(1) gauge group, and generally its couplings to the SM W and Z bosons are assumed to be zero. The Z'_{HVT} boson is a neutral member of a new SU(2) gauge group, i.e. part of a triplet and cannot exist without two new charged heavy bosons, $W'^{\pm}_{HVT}$, with which it is nearly degenerate in mass. New spin-2 resonances, excited states of the graviton, are introduced in the Randall–Sundrum model [10] with a warped extra dimension. In experimental terms the described scenarios would result in a local excess of signal candidates over a smoothly falling dilepton mass spectrum. This search has a clean experimental signature with a fully reconstructable final state and excellent detection efficiency.

This Letter presents a search for a new resonance decaying into two electrons or two muons in 139 fb^{-1} of data collected in proton–proton (pp) collisions at the LHC at a centre-of-mass energy $\sqrt{s} = 13$ TeV. Previous searches with 36.1 fb^{-1} of pp collision data at $\sqrt{s} = 13$ TeV conducted by the ATLAS and CMS experiments [11,12] showed no significant excess and led to lower limits of up to 3.8 TeV for the mass of the Z'_ψ boson. The analysis presented in this Letter, compared with that published in Ref. [11], benefits from: a factor of four increase in integrated luminosity; several improvements in the reconstruction software, including the use of a new dynamical, topological cell-clustering algorithm for electron reconstruction [13] and an improved treatment of the relative alignment of the inner tracker and the muon tracking detectors in the muon reconstruction; the use of invariant-mass sidebands of the expected signal in data to constrain the fit parameters of the background distribution, which is described by a smooth functional form instead of relying on simulation; and a generic

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Table 1
The event generators used for simulation of the signal and background processes. The acronyms ME and PS stand for matrix element and parton shower. The top-quark mass is set to 172.5 GeV.

	ME Generator and ME PDFs	PS and non-perturbative effect with PDFs
Background process		
NLO Drell–Yan	Powheg-Box [23,24], CT10 [25], Photos	Pythia v8.186 [26], CTEQ6L1 [27,28], EvtGen1.2.0
$t\bar{t}$	Powheg-Box, NNPDF3.0NLO [29]	Pythia v8.230, NNPDF23LO [30], EvtGen1.6.0
Single top s-channel, Wt	Powheg-Box, NNPDF3.0NLO	Pythia v8.230, NNPDF23LO, EvtGen1.6.0
Single top t-channel	Powheg-Box, NNPDF3.04fNLO, MadSpin	Pythia v8.230, NNPDF23LO, EvtGen1.6.0
Diboson (WW, WZ and ZZ)	Sherpa 2.1.1 [31], CT10	Sherpa 2.1.1, CT10
Signal process		
LO Drell–Yan	Pythia v8.186, NNPDF23LO	Pythia v8.186, NNPDF23LO, EvtGen1.2.0
Randall–Sundrum $G^* \to \ell\ell$	Pythia v8.210, NNPDF23LO	Pythia v8.210, NNPDF23LO, EvtGen1.2.0
MSSM $gg \to H \to \ell\ell$	Powheg-Box, CT10	Pythia v8.212, CTEQ6L1, EvtGen1.2.0

signal line shape described by a non-relativistic Breit–Wigner function convolved with the detector resolution, which simplifies reinterpretations of the result.

2. ATLAS detector

ATLAS [14–16] is a multipurpose detector with a forward–backward symmetric cylindrical geometry with respect to the LHC beam axis.[1] The innermost layers consist of tracking detectors in the pseudorapidity range $|\eta| < 2.5$. This inner detector (ID) is surrounded by a thin superconducting solenoid that provides a 2 T axial magnetic field. It is enclosed by the electromagnetic and hadronic calorimeters, which cover $|\eta| < 4.9$. The outermost layers of ATLAS consist of an external muon spectrometer (MS) within $|\eta| < 2.7$, incorporating three large toroidal magnetic assemblies with eight coils each. The field integral of the toroids ranges between 2.0 and 6.0 Tm for most of the acceptance. The MS includes precision tracking chambers and fast detectors for triggering. A two-level trigger system [17] reduces the recorded event rate to an average of 1 kHz.

3. Data and simulation

The dataset used in this analysis was collected during LHC Run 2 in stable beam conditions and with all detector systems operating normally. The event quality was checked to remove events with noise bursts or coherent noise in the calorimeters. Events in the dielectron channel were recorded using a dielectron trigger based on the 'very loose' or 'loose' identification criteria [17] with transverse energy (E_T) thresholds between 12 and 24 GeV for both electrons, depending on the data-taking period. Events in the dimuon channel are required to pass at least one of two single-muon triggers: the first requires a transverse momentum (p_T) of at least 50 GeV, while the second has a threshold lowered to 26 GeV but requires the muon candidate to be isolated [17]. The integrated luminosity of the dataset is determined to be 139.0 ± 2.4 fb^{-1}, following a methodology similar to that detailed in Ref. [18], and using the LUCID-2 detector for the baseline luminosity measurements [19], from calibration of the luminosity scale using x-y beam-separation scans.

While the search in this analysis is carried out entirely in a data-driven way, simulated event samples for the signal and background processes are used to determine appropriate functions to fit the data, study background compositions and to evaluate the signal efficiency. The main backgrounds in decreasing order of importance are Drell–Yan (DY), top-quark pair ($t\bar{t}$), single-top-quark and diboson production. Multi-jet and $W+$jets processes in the dielectron channel are estimated with a data-driven method [11]. Multi-jet and $W+$jets processes in the dimuon channel as well as processes with τ-leptons in both channels have a negligible impact and are not considered. The Monte Carlo (MC) event generators for the hard-scatter process, showering and parton distribution functions (PDFs) are listed in Table 1. The 'afterburner' generators such as Photos [20] for the final-state photon radiation (FSR) modelling, MadSpin [21] to preserve top-quark spin correlations, and EvtGen [22], used for the modelling of c- and b-hadron decays, are also reported.

The DY [32] and diboson [33] samples are generated in slices of dilepton mass to increase the sample size in the high-mass region. Next-to-next-to-leading-order (NNLO) corrections in quantum chromodynamic (QCD) theory and next-to-leading-order (NLO) corrections in electroweak (EW) theory, are calculated and applied to the DY events. The corrections are computed with VRAP v0.9 [34] and the CT14 NNLO PDF set [35] in the case of QCD effects whereas they are computed with MCSANC [36] in the case of quantum electrodynamic effects due to initial state radiation, interference between initial and final state radiation, and Sudakov logarithm single-loop corrections. The top-quark samples [37] are normalised to the cross-sections calculated at NNLO in QCD including resummation of the next-to-next-to-leading logarithmic soft gluon terms as provided by Top++2.0 [38].

Spin-1 signal templates are obtained by a matrix-element reweighting [11] of the leading-order (LO) DY samples generated in slices of dilepton mass. These signal templates are used only for cross-section and efficiency calculations. The relative natural width ($\Gamma_{Z'}/m_{Z'}$) for the benchmark models considered varies between 0.5% for Z'_ψ and 3% for Z'_{SSM}. Interference effects between the resonant signal and the background processes are neglected. Higher-order QCD corrections for all the spin-1 signals are computed with the same methodology as for the DY background. For the HVT model, these corrections are not applied, which ensures consistent treatment with the other signal channels in an eventual combination, similar to that described in Ref. [39]. Electroweak corrections are not applied to the signal samples due to their large model dependence. Spin-0 signal efficiencies are obtained from samples of the MSSM gluon–gluon fusion production of a heavy Higgs boson decaying into dilepton pairs, $gg \to H \to \ell\ell$, produced in the mass range $m_H = 400$–1000 GeV and with relative natural width (Γ_H/m_H) varying between zero and 20%. Spin-2 signal efficiencies are obtained from Randall–Sundrum graviton $G^* \to \ell\ell$ samples produced in the mass range $m_{G^*} = 750$–5000 GeV and with coupling strengths, $k/\overline{m}_{\mathrm{Pl}}$, of 0.1, 0.2 and 0.3, where k is a

[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upwards. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

scale that defines the warp factor of the extra dimension and $\overline{m}_{\mathrm{Pl}}$ is the reduced Planck mass.

Simulated event samples include the effect of multiple pp interactions in the same or neighbouring bunch crossings. These effects are collectively referred to as pile-up. The simulation of pile-up collisions was performed with PYTHIA v8.186 using the ATLAS A3 set of tuned parameters [40] and the NNPDF23LO PDF set, and weighted to reproduce the average number of pile-up interactions per bunch crossing observed in data. The generated events were passed through a full detector simulation [41] based on GEANT 4 [42]. Spin-0 and spin-2 MC signal samples were produced with a fast parameterisation of the calorimeter response [43].

Very large generator-level-only MC samples (with more than 55 times the data events) for NLO DY events are used for the background studies described in Section 6. These samples could not be produced with the full detector simulation due to the large number of events required.

4. Event selection

The selection of dilepton events closely follows that described in Ref. [11]. An event is selected if at least one pp interaction vertex is reconstructed. The primary vertex is chosen to be the vertex with the highest summed p_{T}^2 of tracks with transverse momentum $p_{\mathrm{T}} > 0.5$ GeV which are associated with the vertex.

Electron candidates are reconstructed from ID tracks that are matched to clusters of energy deposited in the electromagnetic calorimeter with energy deposition consistent with that of an electromagnetic shower [44]. Reconstructed electrons must have $E_{\mathrm{T}} > 30$ GeV, satisfy $|\eta| < 2.47$ in order to pass through the fine-granularity region of the EM calorimeter, and be outside the range $1.37 < |\eta| < 1.52$ corresponding to the transition region between the barrel and endcap EM calorimeters. The calorimeter granularity in the excluded transition region is reduced, and the presence of significant additional inactive material degrades the electron identification capabilities and energy resolution. The 'medium' electron working point used for the final selection has an identification and reconstruction efficiency for prompt electrons above 92% for $E_{\mathrm{T}} > 80$ GeV.

Muon candidates are identified by matching ID tracks to tracks reconstructed in the MS [45]. Muon candidates must have $p_{\mathrm{T}} > 30$ GeV and $|\eta| < 2.5$. To ensure optimal muon momentum resolution at high p_{T}, the 'high p_{T}' identification working point is used. It requires at least three hits in each of three layers of precision tracking chambers in the MS, and specific regions of the MS where the alignment is suboptimal are vetoed as a precaution. These requirements reject about 80% (13%) of the muon candidates in (outside) the barrel–endcap overlap region, $1.01 < |\eta| < 1.1$. The muon 'high p_{T}' working point has an η-averaged efficiency of 69% at 1 TeV which decreases to 64% at 2.5 TeV due to increased occasional catastrophic energy loss at high p_{T}. Additionally, a 'good muon' selection requires that the uncertainty in the charge-to-momentum ratio of muon candidates is less than a p_{T}-dependent value. This selection is fully efficient below 1 TeV, but introduces an additional inefficiency of 7% at 2.5 TeV.

Electron (muon) candidate tracks must be consistent with the primary vertex both along the beamline, where the longitudinal impact parameter z_0 is required to satisfy $|z_0 \sin\theta| < 0.5$ mm, and in the transverse plane, where the transverse impact parameter significance $|d_0/\sigma(d_0)|$ is required to be less than 5 (3). To reduce background from misidentified jets as well as from light- and heavy-flavour hadron decays inside jets, lepton candidates are required to be isolated. Electrons must pass the 'gradient' isolation working point which targets an E_{T}-dependent value of the isolation efficiency, uniform in η, using a combination of track and calorimeter isolation requirements [44]. For muons, the summed scalar p_{T} of good-quality tracks with $p_{\mathrm{T}} > 1$ GeV originating from the primary vertex within a cone of variable size[2] ΔR around the muon, but excluding the muon-candidate track itself, must be less than 6% of the p_{T} of the muon candidate. The efficiency of this selection is above 99% for both electrons and muons with $p_{\mathrm{T}} > 60$ GeV. Corrections are applied to electron (muon) candidates to match the energy (momentum) scale and resolution between simulation and data. These corrections are derived in an energy independent way for electrons [46]. For muons, the correction is determined as a function of p_{T} up to 300 GeV, from a fit to $Z \to \mu\mu$ data with templates derived from simulation [45]. At high transverse momentum, the calibrations are dominated by corrections extracted from alignment studies, using special runs with the toroidal magnetic field off. Corrections to the lepton efficiencies in the simulation are derived from the data for electron E_{T} (muon p_{T}) up to 150 (200) GeV [44,45]. The simulation is used to extrapolate to higher electron E_{T} (muon p_{T}) and to study systematic effects.

The events are required to contain at least two same-flavour leptons. If additional leptons are present in the event, the two same-flavour leptons with the largest E_{T} (p_{T}) in the electron (muon) channel are selected to form the dilepton pair. If two different-flavour pairs are found, the dielectron pair is kept, because of the better resolution and higher efficiency for electrons. A selected muon pair is required to be oppositely charged. For an electron pair, the opposite-charge requirement is not applied because of the higher probability of charge misidentification for high-E_{T} electrons. The reconstructed mass of the dilepton system after the full analysis selection, $m_{\ell\ell}$, is required to be above 225 GeV to avoid the Z boson peak region, which cannot be described by the same parameterisation as the high-mass part of the dilepton distributions.

5. Reconstructed dilepton mass modelling

The relative dilepton mass resolution is defined as $(m_{\ell\ell} - m_{\ell\ell}^{\mathrm{true}})/m_{\ell\ell}^{\mathrm{true}}$, where $m_{\ell\ell}^{\mathrm{true}}$ is the generated dilepton mass at Born level before FSR. The mass resolution is parameterised as a sum of a Gaussian distribution, which describes the detector response, and a Crystal Ball function composed of a secondary Gaussian distribution with a power-law low-mass tail, which accounts for bremsstrahlung effects in the dielectron channel or for the effect of poorly reconstructed muons. The parameterisation of the relative dilepton mass resolution as a function of $m_{\ell\ell}^{\mathrm{true}}$ is determined by a simultaneous fit of the function described above to NLO DY MC events. The MC sample is separated in 200 $m_{\ell\ell}^{\mathrm{true}}$ bins of equal size on a logarithmic scale in the range of 130 GeV to 6 TeV. This procedure is repeated to evaluate the uncertainty on the fit parameters by shifting individually the lepton energy and momentum scale and resolutions by their uncertainties.

6. Signal and background modelling

A resonant signal is searched for by fitting the data dilepton mass distribution. The fit function consists of a smooth functional form for the background, and a generic signal shape. The generic signal shapes are constructed from non-relativistic Breit–Wigner functions of various widths convolved with the detector resolution, obtained as described in the previous section. The shape of

[2] ΔR has a maximum value of 0.3 and decreases as a function of p_{T} as $10\,\mathrm{GeV}/p_{\mathrm{T}}[\mathrm{GeV}]$.

Table 2
The relative impact of $\pm 1\sigma$ variation of systematic uncertainties on the signal yield in percent for zero (10%) relative width signals at the pole masses of 300 GeV, 2 and 5 TeV for dielectron and dimuon channels. Sources of uncertainties leading to an impact smaller than 0.5% on the signal yield at any point of the mass spectrum are not shown. A signal is injected at the cross-section limit.

Uncertainty source for m_X [GeV]	Dielectron			Dimuon		
	300	2000	5000	300	2000	5000
Spurious signal	±12.5 (12.0)	±4.6 (10.8)	±0.1 (1.0)	±11.7 (11.0)	±3.8 (3.5)	±2.1 (2.2)
Lepton identification	±1.6 (1.6)	±5.6 (5.6)	±5.6 (5.6)	±1.8 (1.8)	$^{+12}_{-10}$ $\left(^{+12}_{-10}\right)$	$^{+25}_{-20}$ $\left(^{+25}_{-20}\right)$
Isolation	±0.3 (0.3)	±1.1 (1.2)	±1.1 (1.1)	±0.4 (0.4)	±0.4 (0.4)	±0.4 (0.5)
Luminosity	±1.7 (1.7)	±1.7 (1.7)	±1.7 (1.7)	±1.7 (1.7)	±1.7 (1.7)	±1.7 (1.7)
Electron energy scale	$^{-1.7}_{-4.0}$ $\left(^{+1.0}_{-1.8}\right)$	$^{-1.9}_{-6.0}$ $\left(^{+1.7}_{-2.9}\right)$	$^{+0.1}_{-0.4}$ (±0.8)	–	–	–
Electron energy resolution	$^{+7.9}_{-8.3}$ $\left(^{+1.1}_{-0.9}\right)$	$^{+9.0}_{-11.8}$ $\left(^{+0.7}_{-0.5}\right)$	$^{+0.4}_{-0.9}$ (±0.1)	–	–	–
Muon ID resolution	–	–	–	$^{+0.8}_{-2.3}$ $\left(^{+0.3}_{-0.8}\right)$	$^{+0.9}_{-1.3}$ $\left(^{+0.7}_{-1.1}\right)$	$^{+0.6}_{-0.4}$ $\left(^{+0.5}_{-0.3}\right)$
Muon MS resolution	–	–	–	$^{+2.8}_{-3.8}$ $\left(^{+1.0}_{-1.3}\right)$	$^{+3.2}_{-3.0}$ $\left(^{+2.6}_{-2.4}\right)$	±2.4 (2.1)
'Good muon' requirement	–	–	–	±0.6 (0.6)	$^{+9.0}_{-8.2}$ $\left(^{+9.0}_{-8.2}\right)$	$^{+55}_{-35}$ $\left(^{+55}_{-35}\right)$

the dilepton invariant mass distribution for a signal resonance with intrinsic width that is negligible compared with the detector resolution (zero-width signal) is obtained from the mass resolution only.

To allow for a generic resonance search, a fiducial region at particle level is defined following the selection criteria applied to the reconstructed lepton candidates: each electron and muon candidate needs to pass $|\eta| < 2.5$ and E_{T} (p_{T}) > 30 GeV, and the dilepton mass has to satisfy $m_{\ell\ell}^{\mathrm{true}} > m_X - 2\Gamma_X$, where m_X and Γ_X represent the pole mass and width of a hypothetical resonance X, respectively. This selection is added in order to reduce the model dependence from off-shell effects.

The nominal combined reconstruction and identification efficiency in the fiducial region is extracted from the DY sample and thus assumes the kinematics of a spin-1 boson. For the dielectron (dimuon) channels, it varies from 64% (54%) at 225 GeV to 74% (38%) at 6 TeV for the zero-width signals. For a spin-1 signal with 10% relative width, the efficiency changes by less than 0.5% relative to a signal with zero width for both channels over most of the considered invariant-mass range. Only above 5 TeV in the dimuon channel are the variations as large as 2% in absolute efficiency. For the spin-0 and spin-2 samples, width-related variations are below 1%. For the dielectron channel, spin-0 and spin-2 efficiencies are higher than the corresponding spin-1 values by at most 4%. For the dimuon channel, efficiencies for spin-0 and spin-2 signals are at most 1% lower than the corresponding spin-1 values. The systematic uncertainties of the overall efficiency are due to the uncertainties in the trigger, isolation, identification, and reconstruction efficiencies.

The smooth functional form for the background is based on fit performance studies on a MC background template. The associated uncertainties are also estimated through these studies. In order to minimise the statistical uncertainties in this procedure, the background template for DY is produced from large-statistics samples simulated only at generator level and smeared by the experimental dilepton mass resolution, described in the previous section, with mass-dependent acceptance and efficiency corrections applied. A similar procedure is applied to the generator-level dilepton mass distribution in the $t\bar{t}$ sample exploiting the larger number of events from the generator-level mass distribution. The distributions from the diboson and single-top simulated samples and, in the electron channel, a template for multi-jet and $W+$jet processes are also considered. All MC-based contributions are scaled by their respective cross-sections and summed together to obtain the background template for the choice of the smooth functional form.

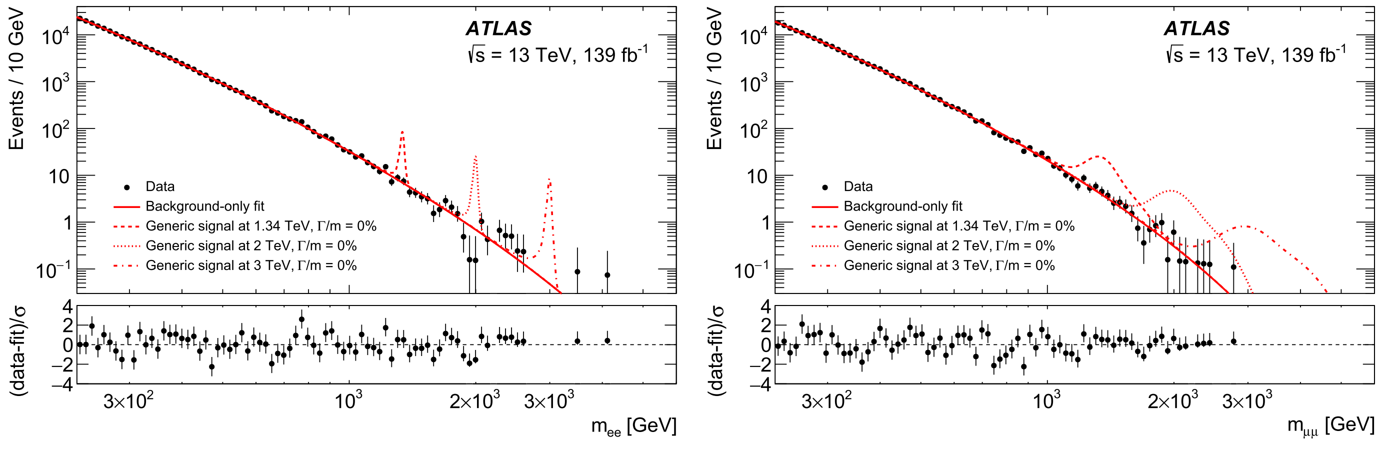
In order to select the background functional form, a fit to the dilepton mass background template is performed, under the signal plus background hypothesis, for various functional forms, following the procedure outlined in Ref. [47]. The chosen functional form is the one with the smallest absolute number of fitted signal events ('spurious signal'), which are determined as a function of $m_{\ell\ell}$:

$$f_{\ell\ell}(m_{\ell\ell}) = f_{\mathrm{BW},Z}(m_{\ell\ell}) \cdot \left(1 - x^c\right)^b \cdot x^{\sum_{i=0}^{3} p_i \log(x)^i}, \qquad (1)$$

where $x = m_{\ell\ell}/\sqrt{s}$ and parameters b and p_i with $i = 0, ..3$ are left free in the fit to data and independent for dielectron and dimuon channels. The parameter c is 1 for the dielectron and 1/3 for the dimuon channel. The function $f_{\mathrm{BW},Z}(m_{\ell\ell})$ is a non-relativistic Breit–Wigner function with $m_Z = 91.1876$ GeV and $\Gamma_Z = 2.4952$ GeV [48]. The normalisation of the background function is such that the integral a corresponds to the total number of background events. To further validate this functional form an extra degree of freedom ($i = 4$) is added to the fit function before the final data analysis, to check if it improves the likelihood value of the fit by more than 2σ. To check the fit stability in the high-mass region, signal injection tests are performed at various mass points. No significant bias in the number of extracted signal events is observed.

Uncertainties related to the background modelling are propagated into the determination of the spurious signal. Smooth templates for systematic shape uncertainties are produced using the same procedure as for the nominal templates. The uncertainties considered include variations due to PDFs [11] and normalisation of the $t\bar{t}$ background component [49]. Uncertainties on the multi-jet and $W+$jet background contributions [11] are also considered in the dielectron channel. For the selected function, the largest spurious signal (accounting for all systematic variations) is required to be less than 30% of the statistical uncertainty in the fitted signal yield (from the background distribution) for the zero-width signal. This criterion is relaxed to 50% for signals of greater width. The systematic uncertainty of the background estimate is mass dependent and corresponds to a functional interpolation between the highest maxima among the spurious-signal-yield distributions for all systematic variations. The spurious-signal yield is calculated independently for the relative signal width assumptions between zero and 10% in steps of 0.5%.

The impact of systematic uncertainties on the signal yield is shown in Table 2. Only systematic uncertainties which change the fitted signal yield by more than 0.5% at any point in the mass spectrum are considered. The largest systematic uncertainty at low mass in both channels originates from the spurious signals. The



(a) (b)

Fig. 1. Distribution of the (a) dielectron and (b) dimuon invariant mass for events passing the full selection. Generic zero-width signal shapes, scaled to 20 times the value of the corresponding expected upper limit at 95% CL on the fiducial cross-section times branching ratio, with pole masses of $m_X = 1.34$, 2 and 3 TeV as well as background-only fits are superimposed. The data points are plotted at the centre of each bin. The error bars indicate statistical uncertainties only. The differences between the data and the fit results in units of standard deviations of the statistical uncertainty are shown in the bottom panels.

largest systematic uncertainty in the dielectron channel at high mass originates from the electron identification efficiency. The uncertainty associated with the 'good muon' requirement is dominant in the dimuon channel at high mass. This uncertainty is estimated with a conservative approach in a dataset collected in 2015–2016, corresponding to 36 fb^{-1}, by comparing efficiencies obtained in data and in simulation.

7. Statistical analysis

The numbers of signal and background events, as a function of the signal mass and width hypothesis, are estimated from simultaneous maximum-likelihood fits of the signal-plus-background models to the data $m_{\ell\ell}$ distribution. Systematic uncertainties are included in the fits via nuisance parameters constrained by penalty terms which are either Gaussian (e.g. energy and momentum scale uncertainties) or log-normal (efficiency and resolution uncertainties). Potential mismodelling of the background estimate is accounted for through an additional nuisance parameter allowing non-zero signal normalisation under the null hypothesis constrained by the measured spurious signal. Dielectron and dimuon channels are considered both as independent channels and in a combined approach, under a lepton-flavour universality assumption [7,8].

The significance of a signal is summarised by a p-value, the probability of observing an excess at least as signal-like as the one observed in data, in the absence of signal. The local p-value of the background-only hypothesis (p_0) is determined from a profile-likelihood-ratio-test statistic [50] as detailed in Ref. [51] in the asymptotic approximation. Global significance values are also computed in the asymptotic approximation to account for the trial factors due to scanning the signal mass hypothesis [52]. Upper limits at the 95% confidence level (CL) are set on the fiducial cross-section times branching ratio into the corresponding dilepton final state, given the integrated luminosity of the data and the signal efficiency. The limits are evaluated with the modified frequentist CL_S method [53] using the asymptotic approximation to the test-statistic distribution [50]. Cross-checks with sampling distributions generated using pseudo-experiments are used to test the accuracy of this approximation for the high-mass part of the dilepton spectra. The approximation is found to lead to limits that are stronger than those obtained with pseudo-experiments above 3 TeV. This effect reaches 25% (35%) at 5 TeV (6 TeV) for the combined dilepton channel. The impact of this approximation on the mass limits is below 100 GeV.

8. Results

The dilepton invariant-mass distributions for the events that pass the full analysis selection are shown in Fig. 1. The event with highest reconstructed mass is a dielectron candidate with $m_{ee} = 4.06$ TeV, formed of two electrons with $E_T = 2.01$ TeV and $E_T = 1.92$ TeV in the barrel region of the calorimeter. The event with highest reconstructed mass in the dimuon channel has an invariant mass of $m_{\mu\mu} = 2.75$ TeV. Both muon candidates are in the barrel section of the muon spectrometer and their transverse momenta are $p_T = 1.82$ TeV and $p_T = 1.04$ TeV.

The fit to data[3] is performed in bins of 1 GeV and uses the function in Eq. (1). In both channels, validation tests using the extension of the functional form described in Section 6 did not yield any significant improvement, so the function in Eq. (1) is used without modification.

The probability that the data are compatible with the background-only hypothesis is shown in Fig. 2 as a function of pole mass for zero-width signals. No significant excess is observed. The largest deviations from the background-only hypothesis in the dielectron, dimuon and combined dilepton channels are observed at masses of 774 GeV, 267 GeV and 264 GeV for zero-width signals with a local p_0 of 2.9 σ, 2.4 σ and 2.3 σ and a global significance of 0.1 σ, 0.3 σ, and zero, respectively.

Fig. 3 shows the upper limits on the fiducial cross-section times branching ratio to two leptons of a single flavour for generic resonances of various relative widths as a function of their mass. The observed limits for pole masses ranging from 250 to 750 GeV are obtained with a spacing of 1 GeV. The granularity is reduced above that mass, but remains below the experimental resolution of the ee channel. The observed limit on the fiducial cross-section times branching ratio ranges from 3.6 (13.1) fb at 250 GeV to about 0.014 (0.018) fb at 6 TeV for the zero (10%) relative width signal in the combined dilepton channel. The impact of systematic uncertainties

[3] The resulting fit parameters for dielectron channel are: $a = 178000 \pm 400$, $b = 1.5 \pm 1.0$, $p_0 = -12.38 \pm 0.09$, $p_1 = -4.295 \pm 0.014$, $p_2 = -0.9191 \pm 0.0027$, $p_3 = -0.0845 \pm 0.0005$; for dimuon channel are: $a = 138700 \pm 400$, $b = 11.8 \pm 0.5$, $p_0 = -7.38 \pm 0.12$, $p_1 = -4.132 \pm 0.017$, $p_2 = -1.0637 \pm 0.0029$, $p_3 = -0.1022 \pm 0.0005$.

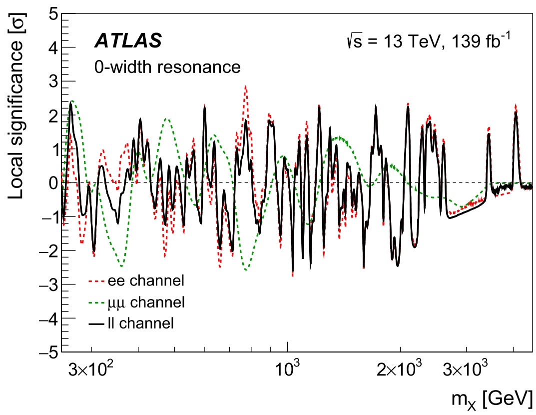


Fig. 2. Probability that the observed spectrum is compatible with the background-only hypothesis for the dielectron, dimuon and combined dilepton channels. The local p_0 is quantified in standard deviations σ as a function of pole mass m_X.

on this search is small across all mass and width assumptions, resulting in the expected limits on the fiducial cross-section times branching ratio to dileptons being (4–7)% weaker than those without systematic uncertainties. As all studied signal spin hypotheses (0, 1, 2) have efficiency values which are consistent within 4%, the limits shown above can be used for reinterpretation of models with such new resonances.

The generic cross-section limits at $\Gamma/m = 0.5\%$, 1.2% and 3.0% are compared with the model predictions of Z'_ψ, Z'_χ and Z'_{SSM}, respectively, to obtain mass limits. The cross-section values for the model predictions are obtained in the fiducial volume, for compatibility with the definition of the generic signal model. Mass limits are calculated as the intersection between the expected and observed limits with the model prediction. Table 3 lists the mass limits for the three tested models in all three channels. These exceed previously reported results [11] by 500–800 GeV.

The generic cross-section limits shown in Fig. 3 are smoothly interpolated via Delaunay triangulation [54] to produce limits in between the tested widths. The results are converted into exclusion contours in the HVT model coupling space presented in Fig. 4, where g_ℓ, g_q and g_h correspond to the coupling strengths between the triplet field and the lepton, quark and Higgs and vector-boson fields, respectively. In the tested $\{g_q, g_\ell\}$ plane the relative width always remains below 10%, and in the $\{g_h, g_f\}$ plane

Table 3
Observed and expected 95% CL lower limits on $m_{Z'}$ for three Z' gauge boson models, quoted to the nearest 100 GeV in the ee and $\mu\mu$ channels as well as their combination ($\ell\ell$).

Model	Lower limits on $m_{Z'}$ [TeV]					
	ee		$\mu\mu$		$\ell\ell$	
	obs	exp	obs	exp	obs	exp
Z'_ψ	4.1	4.3	4.0	4.0	4.5	4.5
Z'_χ	4.6	4.6	4.2	4.2	4.8	4.8
Z'_{SSM}	4.9	4.9	4.5	4.5	5.1	5.1

($g_f \equiv g_\ell = g_q$) it only exceeds 10% in regions ($|g_f| > 0.9$ and $|g_h| > 2.5$) well outside the limit contours. The observed limits can be compared with the limits obtained for the combination of the $\ell\ell$ and $\ell\nu$ channels in Ref. [39] (provided in brackets): for $g_h = 0$ and $m_{Z'_{\mathrm{HVT}}} = 3$ TeV, 4 TeV and 5 TeV the $|g_f|$ values above 0.07 (0.06), 0.23 (0.15) and 0.49 (0.42) are excluded at 95% CL, respectively. The resulting dilepton-only limits are slightly weaker than those for the $\ell\ell$ and $\ell\nu$ channels combined, even with a four times larger dataset, because of the higher $W'_{\mathrm{HVT}} \to \ell\nu$ cross-section in this model.

A complete set of tables and figures (including additional results for the dielectron and dimuon channels) are available at the Durham HepData repository [55].

9. Conclusions

The ATLAS detector at LHC is used to search for new resonances with mass larger than 250 GeV decaying into a pair of electrons or muons in 139 fb^{-1} of proton–proton collision data at a centre-of-mass energy $\sqrt{s} = 13$ TeV. A functional form is fitted to the dilepton invariant-mass distribution in data events to model the contribution from background processes. A generic signal shape is used to determine the significance of observed deviations from the background estimate. No significant deviation is observed. Limits are set on the fiducial cross-section times branching ratio to dielectrons and dimuons for generic resonances with a relative natural width in the range of zero to 10%. These limits are shown to be applicable to spin-0, spin-1 and spin-2 signal hypotheses. Limits on the Heavy Vector Triplet model couplings and on the masses of vector resonances are inferred. In particular, the results imply a lower limit of 4.5 (5.1) TeV on $m_{Z'}$ for the Z'_ψ (Z'_{SSM}) boson at 95% confidence level. These are the most stringent limits to date.

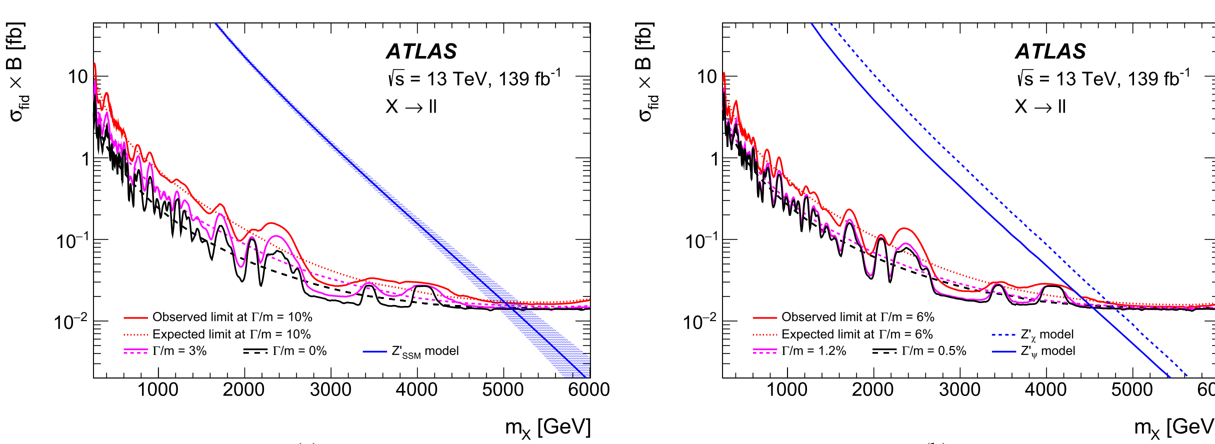
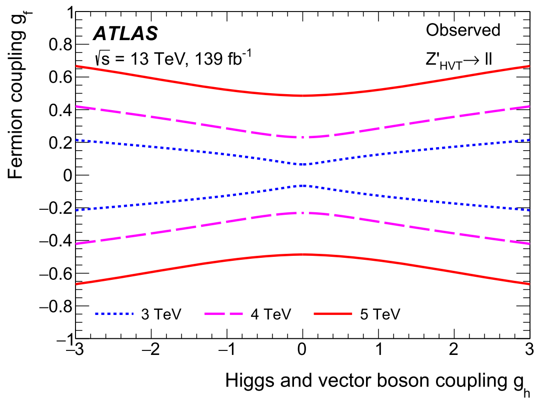
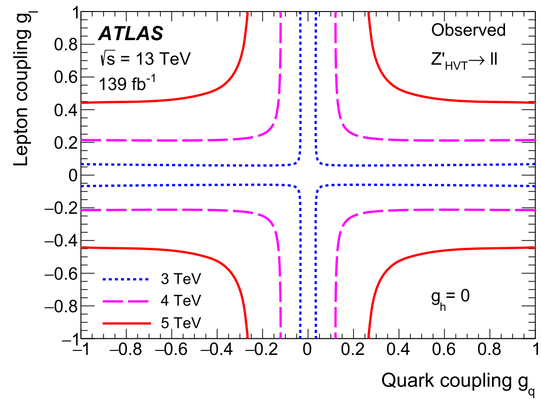


Fig. 3. Upper limits at 95% CL on the fiducial cross-section times branching ratio as a function of pole mass for (a) the zero-width, 3%, 10% and (b) 0.5%, 1.2%, 6% relative width signals for the combined dilepton channel. Observed limits are shown as a solid line and expected limits as a dotted/dashed line. Also shown are theoretical cross-sections for (a) Z'_{SSM} ($\Gamma/m = 3.0\%$) and (b) Z'_χ ($\Gamma/m = 1.2\%$) and Z'_ψ ($\Gamma/m = 0.5\%$) in the fiducial region. The signal theoretical uncertainties are shown as a band on the Z'_{SSM} theory line and are derived as in Ref. [11]. They are shown for illustration purposes, but are not included in the limit calculation.



(a)



(b)

Fig. 4. Observed 95% exclusion contours in the HVT parameter space (a) $\{g_h, g_f\}$ with $g_f \equiv g_\ell = g_q$ and (b) $\{g_q, g_\ell\}$ with g_h set to zero, for resonance masses of 3, 4, and 5 TeV for the dilepton channel. The area outside the curves is excluded.

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Chelkov [79,aw], M.A. Chelstowska [36], B. Chen [78],

C. Chen [60a], C.H. Chen [78], H. Chen [29], J. Chen [60a], J. Chen [39], S. Chen [137], S.J. Chen [15c], X. Chen [15b,av], Y. Chen [82], Y-H. Chen [46], H.C. Cheng [63a], H.J. Cheng [15a,15d], A. Cheplakov [79], E. Cheremushkina [123], R. Cherkaoui El Moursli [35e], E. Cheu [7], K. Cheung [64], T.J.A. Chevalérias [145], L. Chevalier [145], V. Chiarella [51], G. Chiarelli [71a], G. Chiodini [67a], A.S. Chisholm [36,21], A. Chitan [27b], I. Chiu [163], Y.H. Chiu [176], M.V. Chizhov [79], K. Choi [65], A.R. Chomont [72a,72b], S. Chouridou [162], Y.S. Chow [120], M.C. Chu [63a], J. Chudoba [141], A.J. Chuinard [103], J.J. Chwastowski [84], L. Chytka [130], K.M. Ciesla [84], D. Cinca [47], V. Cindro [91], I.A. Cioară [27b], A. Ciocio [18], F. Cirotto [69a,69b], Z.H. Citron [180], M. Citterio [68a], D.A. Ciubotaru [27b], B.M. Ciungu [167], A. Clark [54], M.R. Clark [39], P.J. Clark [50], C. Clement [45a,45b], Y. Coadou [101], M. Cobal [66a,66c], A. Coccaro [55b], J. Cochran [78], H. 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D'Amico [74a,74b], J. Damp [99], J.R. Dandoy [137], M.F. Daneri [30], N.P. Dang [181], N.D Dann [100], M. Danninger [175], V. Dao [36], G. Darbo [55b], O. Dartsi [5], A. Dattagupta [131], T. Daubney [46], S. D'Auria [68a,68b], W. Davey [24], C. David [46], T. Davidek [143], D.R. Davis [49], E. Dawe [104], I. Dawson [149], K. De [8], R. De Asmundis [69a], M. De Beurs [120], S. De Castro [23b,23a], S. De Cecco [72a,72b], N. De Groot [119], P. de Jong [120], H. De la Torre [106], A. De Maria [15c], D. De Pedis [72a], A. De Salvo [72a], U. De Sanctis [73a,73b], M. De Santis [73a,73b], A. De Santo [156], K. De Vasconcelos Corga [101], J.B. De Vivie De Regie [132], C. Debenedetti [146], D.V. Dedovich [79], A.M. Deiana [42], M. Del Gaudio [41b,41a], J. Del Peso [98], Y. Delabat Diaz [46], D. Delgove [132], F. Deliot [145,q], C.M. Delitzsch [7], M. Della Pietra [69a,69b], D. Della Volpe [54], A. Dell'Acqua [36], L. Dell'Asta [73a,73b], M. Delmastro [5], C. Delporte [132], P.A. Delsart [58], D.A. DeMarco [167], S. Demers [183], M. Demichev [79], G. Demontigny [109], S.P. Denisov [123], D. Denysiuk [120], L. D'Eramo [136], D. Derendarz [84], J.E. Derkaoui [35d], F. Derue [136], P. Dervan [90], K. Desch [24], C. Deterre [46], K. Dette [167], C. Deutsch [24], M.R. Devesa [30], P.O. Deviveiros [36], A. Dewhurst [144], S. Dhaliwal [26], F.A. Di Bello [54], A. Di Ciaccio [73a,73b], L. Di Ciaccio [5], W.K. Di Clemente [137], C. Di Donato [69a,69b], A. Di Girolamo [36], G. Di Gregorio [71a,71b], B. Di Micco [74a,74b], R. Di Nardo [102], K.F. Di Petrillo [59], R. Di Sipio [167], D. Di Valentino [34], C. Diaconu [101], F.A. Dias [40], T. Dias Do Vale [140a], M.A. Diaz [147a], J. Dickinson [18], E.B. Diehl [105], J. Dietrich [19], S. Díez Cornell [46], A. Dimitrievska [18], W. Ding [15b], J. Dingfelder [24], F. Dittus [36], F. Djama [101], T. Djobava [159b], J.I. Djuvsland [17], M.A.B. Do Vale [80c], M. Dobre [27b], D. Dodsworth [26], C. Doglioni [96], J. 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Ellinghaus [182], A.A. Elliot [92], N. Ellis [36], J. Elmsheuser [29], M. Elsing [36], D. Emeliyanov [144], A. Emerman [39], Y. Enari [163], J.S. Ennis [178], M.B. Epland [49], J. Erdmann [47], A. Ereditato [20], M. Errenst [36], M. Escalier [132], C. Escobar [174], O. Estrada Pastor [174], E. Etzion [161], H. Evans [65], A. Ezhilov [138], F. Fabbri [57], L. Fabbri [23b,23a], V. Fabiani [119], G. Facini [94], R.M. Faisca Rodrigues Pereira [140a], R.M. Fakhrutdinov [123], S. Falciano [72a], P.J. Falke [5], S. Falke [5], J. Faltova [143], Y. Fang [15a], Y. Fang [15a], G. Fanourakis [44], M. Fanti [68a,68b], A. Farbin [8], A. Farilla [74a], E.M. Farina [70a,70b], T. Farooque [106], S. Farrell [18], S.M. Farrington [178], P. Farthouat [36], F. Fassi [35e], P. Fassnacht [36], D. Fassouliotis [9], M. Faucci Giannelli [50], W.J. Fawcett [32], L. Fayard [132], O.L. Fedin [138,o], W. Fedorko [175], M. Feickert [42], S. Feigl [134], L. Feligioni [101], A. Fell [149], C. Feng [60b], E.J. 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F. Filthaut [119], K.D. Finelli [25], M.C.N. Fiolhais [140a], L. Fiorini [174], F. Fischer [114], W.C. Fisher [106], I. Fleck [151], P. Fleischmann [105], R.R.M. Fletcher [137], T. Flick [182], B.M. Flierl [114], L.F. Flores [137], L.R. Flores Castillo [63a], F.M. Follega [75a,75b], N. Fomin [17], J.H. Foo [167], G.T. Forcolin [75a,75b], A. Formica [145], F.A. Förster [14], A.C. Forti [100], A.G. Foster [21], M.G. Foti [135], D. Fournier [132], H. Fox [89], P. Francavilla [71a,71b], S. Francescato [72a,72b], M. Franchini [23b,23a], S. Franchino [61a], D. Francis [36], L. Franconi [20], M. Franklin [59], A.N. Fray [92], B. Freund [109], W.S. Freund [80b], E.M. Freundlich [47], D.C. Frizzell [128], D. Froidevaux [36], J.A. Frost [135], C. Fukunaga [164], E. Fullana Torregrosa [174], E. Fumagalli [55b,55a], T. Fusayasu [116], J. Fuster [174], A. Gabrielli [23b,23a], A. Gabrielli [18], G.P. Gach [83a], S. Gadatsch [54], P. Gadow [115], G. Gagliardi [55b,55a], L.G. Gagnon [109], C. Galea [27b], B. Galhardo [140a], G.E. Gallardo [135], E.J. Gallas [135], B.J. Gallop [144], P. Gallus [142], G. Galster [40], R. Gamboa Goni [92], K.K. Gan [126], S. Ganguly [180], J. Gao [60a], Y. Gao [90], Y.S. Gao [31,l], C. García [174], J.E. García Navarro [174], J.A. García Pascual [15a], C. Garcia-Argos [52], M. Garcia-Sciveres [18], R.W. Gardner [37], N. Garelli [153], S. Gargiulo [52], V. Garonne [134], A. Gaudiello [55b,55a], G. Gaudio [70a], I.L. Gavrilenko [110], A. Gavrilyuk [111], C. Gay [175], G. Gaycken [24], E.N. Gazis [10], A.A. Geanta [27b], C.N.P. Gee [144], J. Geisen [53], M. Geisen [99], M.P. Geisler [61a], C. Gemme [55b], M.H. Genest [58], C. Geng [105], S. Gentile [72a,72b], S. George [93], T. Geralis [44], D. Gerbaudo [14], L.O. Gerlach [53], P. Gessinger-Befurt [99], G. Gessner [47], S. Ghasemi [151], M. Ghasemi Bostanabad [176], M. Ghneimat [24], A. Ghosh [77], B. Giacobbe [23b], S. Giagu [72a,72b], N. Giangiacomi [23b,23a], P. Giannetti [71a], A. Giannini [69a,69b], S.M. Gibson [93], M. Gignac [146], D. Gillberg [34], G. Gilles [182], D.M. Gingrich [3,ax], M.P. Giordani [66a,66c], F.M. Giorgi [23b], P.F. Giraud [145], G. Giugliarelli [66a,66c], D. Giugni [68a], F. Giuli [73a,73b], S. Gkaitatzis [162], I. Gkialas [9,h], E.L. Gkougkousis [14], P. Gkountoumis [10], L.K. Gladilin [113], C. Glasman [98], J. Glatzer [14], P.C.F. Glaysher [46], A. Glazov [46], M. Goblirsch-Kolb [26], S. Goldfarb [104], T. Golling [54], D. Golubkov [123], A. Gomes [140a,140b], R. Goncalves Gama [53], R. Gonçalo [140a,140b], G. Gonella [52], L. Gonella [21], A. Gongadze [79], F. Gonnella [21], J.L. Gonski [59], S. González de la Hoz [174], S. Gonzalez-Sevilla [54], G.R. Gonzalvo Rodriguez [174], L. Goossens [36], P.A. Gorbounov [111], H.A. Gordon [29], B. Gorini [36], E. Gorini [67a,67b], A. Gorišek [91], A.T. Goshaw [49], C. Gössling [47], M.I. Gostkin [79], C.A. Gottardo [24], M. Gouighri [35b], D. Goujdami [35c], A.G. Goussiou [148], N. Govender [33b,a], C. Goy [5], E. Gozani [160], I. Grabowska-Bold [83a], E.C. Graham [90], J. Gramling [171], E. Gramstad [134], S. Grancagnolo [19], M. Grandi [156], V. Gratchev [138], P.M. Gravila [27f], F.G. Gravili [67a,67b], C. Gray [57], H.M. Gray [18], C. Grefe [24], K. Gregersen [96], I.M. Gregor [46], P. Grenier [153], K. Grevtsov [46], N.A. Grieser [128], J. Griffiths [8], A.A. Grillo [146], K. Grimm [31,k], S. Grinstein [14,x], J.-F. Grivaz [132], S. Groh [99], E. Gross [180], J. Grosse-Knetter [53], Z.J. Grout [94], C. Grud [105], A. Grummer [118], L. Guan [105], W. Guan [181], J. Guenther [36], A. Guerguichon [132], F. Guescini [168a], D. Guest [171], R. Gugel [52], B. Gui [126], T. Guillemin [5], S. Guindon [36], U. Gul [57], J. Guo [60c], W. Guo [105], Y. Guo [60a,s], Z. Guo [101], R. Gupta [46], S. Gurbuz [12c], G. Gustavino [128], P. Gutierrez [128], C. Gutschow [94], C. Guyot [145], M.P. Guzik [83a], C. Gwenlan [135], C.B. Gwilliam [90], A. Haas [124], C. Haber [18], H.K. Hadavand [8], N. Haddad [35e], A. Hadef [60a], S. Hageböck [36], M. Hagihara [169], M. Haleem [177], J. Haley [129], G. Halladjian [106], G.D. Hallewell [101], K. Hamacher [182], P. Hamal [130], K. Hamano [176], H. Hamdaoui [35e], G.N. Hamity [149], K. Han [60a,ak], L. Han [60a], S. Han [15a,15d], K. Hanagaki [81,v], M. Hance [146], D.M. Handl [114], B. Haney [137], R. Hankache [136], P. Hanke [61a], E. Hansen [96], J.B. Hansen [40], J.D. Hansen [40], M.C. Hansen [24], P.H. Hansen [40], E.C. Hanson [100], K. Hara [169], A.S. Hard [181], T. Harenberg [182], S. Harkusha [107], P.F. Harrison [178], N.M. Hartmann [114], Y. Hasegawa [150], A. Hasib [50], S. Hassani [145], S. Haug [20], R. Hauser [106], L.B. Havener [39], M. Havranek [142], C.M. Hawkes [21], R.J. Hawkings [36], D. Hayden [106], C. Hayes [155], R.L. Hayes [175], C.P. Hays [135], J.M. Hays [92], H.S. Hayward [90], S.J. Haywood [144], F. He [60a], M.P. Heath [50], V. Hedberg [96], L. Heelan [8], S. Heer [24], K.K. Heidegger [52], W.D. Heidorn [78], J. Heilman [34], S. Heim [46], T. Heim [18], B. Heinemann [46,as], J.J. Heinrich [131], L. Heinrich [36], C. Heinz [56], J. Hejbal [141], L. Helary [61b], A. Held [175], S. Hellesund [134], C.M. Helling [146], S. Hellman [45a,45b], C. Helsens [36], R.C.W. Henderson [89], Y. Heng [181], S. Henkelmann [175], A.M. Henriques Correia [36], G.H. Herbert [19], H. Herde [26], V. Herget [177], Y. Hernández Jiménez [33c], H. Herr [99], M.G. Herrmann [114], T. Herrmann [48], G. Herten [52], R. Hertenberger [114], L. Hervas [36], T.C. Herwig [137], G.G. Hesketh [94], N.P. Hessey [168a], A. Higashida [163], S. Higashino [81], E. Higón-Rodriguez [174], K. Hildebrand [37], E. Hill [176], J.C. Hill [32], K.K. Hill [29], K.H. Hiller [46], S.J. Hillier [21], M. Hils [48], I. Hinchliffe [18], F. Hinterkeuser [24], M. Hirose [133], S. Hirose [52], D. Hirschbuehl [182], B. Hiti [91], O. Hladik [141], D.R. Hlaluku [33c], X. Hoad [50], J. Hobbs [155], N. Hod [180], M.C. Hodgkinson [149], A. Hoecker [36], F. Hoenig [114], D. Hohn [52], D. Hohov [132], T.R. Holmes [37], M. Holzbock [114], L.B.A.H Hommels [32], S. Honda [169], T. Honda [81], T.M. Hong [139],

A. Hönle [115], B.H. Hooberman [173], W.H. Hopkins [6], Y. Horii [117], P. Horn [48], A.J. Horton [152], L.A. Horyn [37], J-Y. Hostachy [58], A. Hostiuc [148], S. Hou [158], A. Hoummada [35a], J. Howarth [100], J. Hoya [88], M. Hrabovsky [130], J. Hrdinka [76], I. Hristova [19], J. Hrivnac [132], A. Hrynevich [108], T. Hryn'ova [5], P.J. Hsu [64], S.-C. Hsu [148], Q. Hu [29], S. Hu [60c], Y. Huang [15a], Z. Hubacek [142], F. Hubaut [101], M. Huebner [24], F. Huegging [24], T.B. Huffman [135], M. Huhtinen [36], R.F.H. Hunter [34], P. Huo [155], A.M. Hupe [34], N. Huseynov [79,af], J. Huston [106], J. Huth [59], R. Hyneman [105], S. Hyrych [28a], G. Iacobucci [54], G. Iakovidis [29], I. Ibragimov [151], L. Iconomidou-Fayard [132], Z. Idrissi [35e], P.I. Iengo [36], R. Ignazzi [40], O. Igonkina [120,z,∗], R. Iguchi [163], T. Iizawa [54], Y. Ikegami [81], M. Ikeno [81], D. Iliadis [162], N. Ilic [119], F. Iltzsche [48], G. Introzzi [70a,70b], M. Iodice [74a], K. Iordanidou [39], V. Ippolito [72a,72b], M.F. Isacson [172], M. Ishino [163], M. Ishitsuka [165], W. Islam [129], C. Issever [135], S. Istin [160], F. Ito [169], J.M. Iturbe Ponce [63a], R. Iuppa [75a,75b], A. Ivina [180], H. Iwasaki [81], J.M. Izen [43], V. Izzo [69a], P. Jacka [141], P. Jackson [1], R.M. Jacobs [24], V. Jain [2], G. Jäkel [182], K.B. Jakobi [99], K. Jakobs [52], S. Jakobsen [76], T. Jakoubek [141], J. Jamieson [57], K.W. Janas [83a], R. Jansky [54], J. Janssen [24], M. Janus [53], P.A. Janus [83a], G. Jarlskog [96], N. Javadov [79,af], T. Javůrek [36], M. Javurkova [52], F. Jeanneau [145], L. Jeanty [131], J. Jejelava [159a,ag], A. Jelinskas [178], P. Jenni [52,b], J. Jeong [46], N. Jeong [46], S. Jézéquel [5], H. Ji [181], J. Jia [155], H. Jiang [78], Y. Jiang [60a], Z. Jiang [153,p], S. Jiggins [52], F.A. Jimenez Morales [38], J. Jimenez Pena [174], S. Jin [15c], A. Jinaru [27b], O. Jinnouchi [165], H. Jivan [33c], P. Johansson [149], K.A. Johns [7], C.A. Johnson [65], K. Jon-And [45a,45b], R.W.L. Jones [89], S.D. Jones [156], S. Jones [7], T.J. Jones [90], J. Jongmanns [61a], P.M. Jorge [140a], J. Jovicevic [36], X. Ju [18], J.J. Junggeburth [115], A. Juste Rozas [14,x], A. Kaczmarska [84], M. Kado [72a,72b], H. Kagan [126], M. Kagan [153], C. Kahra [99], T. Kaji [179], E. Kajomovitz [160], C.W. Kalderon [96], A. Kaluza [99], A. Kamenshchikov [123], L. Kanjir [91], Y. Kano [163], V.A. Kantserov [112], J. Kanzaki [81], L.S. Kaplan [181], D. Kar [33c], M.J. Kareem [168b], E. Karentzos [10], S.N. Karpov [79], Z.M. Karpova [79], V. Kartvelishvili [89], A.N. Karyukhin [123], L. Kashif [181], R.D. Kass [126], A. Kastanas [45a,45b], Y. Kataoka [163], C. Kato [60d,60c], J. Katzy [46], K. Kawade [82], K. Kawagoe [87], T. Kawaguchi [117], T. Kawamoto [163], G. Kawamura [53], E.F. Kay [176], V.F. Kazanin [122b,122a], R. Keeler [176], R. Kehoe [42], J.S. Keller [34], E. Kellermann [96], D. Kelsey [156], J.J. Kempster [21], J. Kendrick [21], O. Kepka [141], S. Kersten [182], B.P. Kerševan [91], S. Ketabchi Haghighat [167], M. Khader [173], F. Khalil-Zada [13], M. Khandoga [145], A. Khanov [129], A.G. Kharlamov [122b,122a], T. Kharlamova [122b,122a], E.E. Khoda [175], A. Khodinov [166], T.J. Khoo [54], E. Khramov [79], J. Khubua [159b], S. Kido [82], M. Kiehn [54], C.R. Kilby [93], Y.K. Kim [37], N. Kimura [66a,66c], O.M. Kind [19], B.T. King [90,∗], D. Kirchmeier [48], J. Kirk [144], A.E. Kiryunin [115], T. Kishimoto [163], D.P. Kisliuk [167], V. Kitali [46], O. Kivernyk [5], E. Kladiva [28b,∗], T. Klapdor-Kleingrothaus [52], M.H. Klein [105], M. Klein [90], U. Klein [90], K. Kleinknecht [99], P. Klimek [121], A. Klimentov [29], T. Klingl [24], T. Klioutchnikova [36], F.F. Klitzner [114], P. Kluit [120], S. Kluth [115], E. Kneringer [76], E.B.F.G. Knoops [101], A. Knue [52], D. Kobayashi [87], T. Kobayashi [163], M. Kobel [48], M. Kocian [153], P. Kodys [143], P.T. Koenig [24], T. Koffas [34], N.M. Köhler [115], T. Koi [153], M. 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T. LeCompte [6], F. Ledroit-Guillon [58], C.A. Lee [29], G.R. Lee [17], L. Lee [59], S.C. Lee [158], S.J. Lee [34],
B. Lefebvre [168a], M. Lefebvre [176], F. Legger [114], C. Leggett [18], K. Lehmann [152], N. Lehmann [182],
G. Lehmann Miotto [36], W.A. Leight [46], A. Leisos [162,w], M.A.L. Leite [80d], R. Leitner [143], D. Lellouch [180,*],
K.J.C. Leney [42], T. Lenz [24], B. Lenzi [36], R. Leone [7], S. Leone [71a], C. Leonidopoulos [50], A. Leopold [136],
G. Lerner [156], C. Leroy [109], R. Les [167], C.G. Lester [32], M. Levchenko [138], J. Levêque [5], D. Levin [105],
L.J. Levinson [180], D.J. Lewis [21], B. Li [15b], B. Li [105], C-Q. Li [60a], F. Li [60c], H. Li [60a], H. Li [60b], J. Li [60c], K. Li [153],
L. Li [60c], M. Li [15a], Q. Li [15a,15d], Q.Y. Li [60a], S. Li [60d,60c], X. Li [46], Y. Li [46], Z. Li [60b], Z. Liang [15a], B. Liberti [73a],
A. Liblong [167], K. Lie [63c], S. Liem [120], C.Y. Lin [32], K. Lin [106], T.H. Lin [99], R.A. Linck [65], J.H. Lindon [21],
A.L. Lionti [54], E. Lipeles [137], A. Lipniacka [17], M. Lisovyi [61b], T.M. Liss [173,au], A. Lister [175], A.M. Litke [146],
J.D. Little [8], B. Liu [78,ac], B.L Liu [6], H.B. Liu [29], H. Liu [105], J.B. Liu [60a], J.K.K. Liu [135], K. Liu [136], M. Liu [60a],
P. Liu [18], Y. Liu [15a,15d], Y.L. Liu [105], Y.W. Liu [60a], M. Livan [70a,70b], A. Lleres [58], J. Llorente Merino [15a],
S.L. Lloyd [92], C.Y. Lo [63b], F. Lo Sterzo [42], E.M. Lobodzinska [46], P. Loch [7], S. Loffredo [73a,73b], T. Lohse [19],
K. Lohwasser [149], M. Lokajicek [141], J.D. Long [173], R.E. Long [89], L. Longo [36], K.A. Looper [126], J.A. Lopez [147b],
I. Lopez Paz [100], A. Lopez Solis [149], J. Lorenz [114], N. Lorenzo Martinez [5], M. Losada [22], P.J. Lösel [114],
A. Lösle [52], X. Lou [46], X. Lou [15a], A. Lounis [132], J. Love [6], P.A. Love [89], J.J. Lozano Bahilo [174], M. Lu [60a],
Y.J. Lu [64], H.J. Lubatti [148], C. Luci [72a,72b], A. Lucotte [58], C. Luedtke [52], F. Luehring [65], I. Luise [136],
L. Luminari [72a], B. Lund-Jensen [154], M.S. Lutz [102], D. Lynn [29], R. Lysak [141], E. Lytken [96], F. Lyu [15a],
V. Lyubushkin [79], T. Lyubushkina [79], H. Ma [29], L.L. Ma [60b], Y. Ma [60b], G. Maccarrone [51], A. Macchiolo [115],
C.M. Macdonald [149], J. Machado Miguens [137], D. Madaffari [174], R. Madar [38], W.F. Mader [48], N. Madysa [48],
J. Maeda [82], K. Maekawa [163], S. Maeland [17], T. Maeno [29], M. Maerker [48], A.S. Maevskiy [113], V. Magerl [52],
N. Magini [78], D.J. Mahon [39], C. Maidantchik [80b], T. Maier [114], A. Maio [140a,140b,140d], O. Majersky [28a],
S. Majewski [131], Y. Makida [81], N. Makovec [132], B. Malaescu [136], Pa. Malecki [84], V.P. Maleev [138], F. Malek [58],
U. Mallik [77], D. Malon [6], C. Malone [32], S. Maltezos [10], S. Malyukov [36], J. Mamuzic [174], G. Mancini [51],
I. Mandić [91], L. Manhaes de Andrade Filho [80a], I.M. Maniatis [162], J. Manjarres Ramos [48], K.H. Mankinen [96],
A. Mann [114], A. Manousos [76], B. Mansoulie [145], I. Manthos [162], S. Manzoni [120], A. Marantis [162],
G. Marceca [30], L. Marchese [135], G. Marchiori [136], M. Marcisovsky [141], C. Marcon [96], C.A. Marin Tobon [36],
M. Marjanovic [38], F. Marroquim [80b], Z. Marshall [18], M.U.F Martensson [172], S. Marti-Garcia [174],
C.B. Martin [126], T.A. Martin [178], V.J. Martin [50], B. Martin dit Latour [17], L. Martinelli [74a,74b], M. Martinez [14,x],
V.I. Martinez Outschoorn [102], S. Martin-Haugh [144], V.S. Martoiu [27b], A.C. Martyniuk [94], A. Marzin [36],
S.R. Maschek [115], L. Masetti [99], T. Mashimo [163], R. Mashinistov [110], J. Masik [100], A.L. Maslennikov [122b,122a],
L.H. Mason [104], L. Massa [73a,73b], P. Massarotti [69a,69b], P. Mastrandrea [71a,71b], A. Mastroberardino [41b,41a],
T. Masubuchi [163], A. Matic [114], P. Mättig [24], J. Maurer [27b], B. Maček [91], S.J. Maxfield [90],
D.A. Maximov [122b,122a], R. Mazini [158], I. Maznas [162], S.M. Mazza [146], S.P. Mc Kee [105], T.G. McCarthy [115],
L.I. McClymont [94], W.P. McCormack [18], E.F. McDonald [104], J.A. Mcfayden [36], M.A. McKay [42],
K.D. McLean [176], S.J. McMahon [144], P.C. McNamara [104], C.J. McNicol [178], R.A. McPherson [176,ad],
J.E. Mdhluli [33c], Z.A. Meadows [102], S. Meehan [148], T. Megy [52], S. Mehlhase [114], A. Mehta [90], T. Meideck [58],
B. Meirose [43], D. Melini [174], B.R. Mellado Garcia [33c], J.D. Mellenthin [53], M. Melo [28a], F. Meloni [46],
A. Melzer [24], S.B. Menary [100], E.D. Mendes Gouveia [140a,140e], L. Meng [36], X.T. Meng [105], S. Menke [115],
E. Meoni [41b,41a], S. Mergelmeyer [19], S.A.M. Merkt [139], C. Merlassino [20], P. Mermod [54], L. Merola [69a,69b],
C. Meroni [68a], O. Meshkov [113,110], J.K.R. Meshreki [151], A. Messina [72a,72b], J. Metcalfe [6], A.S. Mete [171],
C. Meyer [65], J. Meyer [160], J-P. Meyer [145], H. Meyer Zu Theenhausen [61a], F. Miano [156], R.P. Middleton [144],
L. Mijović [50], G. Mikenberg [180], M. Mikestikova [141], M. Mikuž [91], H. Mildner [149], M. Milesi [104], A. Milic [167],
D.A. Millar [92], D.W. Miller [37], A. Milov [180], D.A. Milstead [45a,45b], R.A. Mina [153,p], A.A. Minaenko [123],
M. Miñano Moya [174], I.A. Minashvili [159b], A.I. Mincer [124], B. Mindur [83a], M. Mineev [79], Y. Minegishi [163],
Y. Ming [181], L.M. Mir [14], A. Mirto [67a,67b], K.P. Mistry [137], T. Mitani [179], J. Mitrevski [114], V.A. Mitsou [174],
M. Mittal [60c], A. Miucci [20], P.S. Miyagawa [149], A. Mizukami [81], J.U. Mjörnmark [96], T. Mkrtchyan [184],
M. Mlynarikova [143], T. Moa [45a,45b], K. Mochizuki [109], P. Mogg [52], S. Mohapatra [39], R. Moles-Valls [24],
M.C. Mondragon [106], K. Mönig [46], J. Monk [40], E. Monnier [101], A. Montalbano [152], J. Montejo Berlingen [36],
M. Montella [94], F. Monticelli [88], S. Monzani [68a], N. Morange [132], D. Moreno [22], M. Moreno Llácer [36],
C. Moreno Martinez [14], P. Morettini [55b], M. Morgenstern [120], S. Morgenstern [48], D. Mori [152], M. Morii [59],
M. Morinaga [179], V. Morisbak [134], A.K. Morley [36], G. Mornacchi [36], A.P. Morris [94], L. Morvaj [155],
P. Moschovakos [36], B. Moser [120], M. Mosidze [159b], T. Moskalets [145], H.J. Moss [149], J. Moss [31,m],

K. Motohashi [165], E. Mountricha [36], E.J.W. Moyse [102], S. Muanza [101], J. Mueller [139], R.S.P. Mueller [114], D. Muenstermann [89], G.A. Mullier [96], J.L. Munoz Martinez [14], F.J. Munoz Sanchez [100], P. Murin [28b], W.J. Murray [178,144], A. Murrone [68a,68b], M. Muškinja [18], C. Mwewa [33a], A.G. Myagkov [123,ao], J. Myers [131], M. Myska [142], B.P. Nachman [18], O. Nackenhorst [47], A. Nag Nag [48], K. Nagai [135], K. Nagano [81], Y. Nagasaka [62], M. Nagel [52], E. Nagy [101], A.M. Nairz [36], Y. Nakahama [117], K. Nakamura [81], T. Nakamura [163], I. Nakano [127], H. Nanjo [133], F. Napolitano [61a], R.F. Naranjo Garcia [46], R. Narayan [11], D.I. Narrias Villar [61a], I. Naryshkin [138], T. Naumann [46], G. Navarro [22], H.A. Neal [105,*], P.Y. Nechaeva [110], F. Nechansky [46], T.J. Neep [21], A. Negri [70a,70b], M. Negrini [23b], C. Nellist [53], M.E. Nelson [135], S. Nemecek [141], P. Nemethy [124], M. Nessi [36,d], M.S. Neubauer [173], M. Neumann [182], P.R. 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Paredes Hernandez [63b], S.R. Paredes Saenz [135], B. Parida [166], T.H. Park [167], A.J. Parker [89], M.A. Parker [32], F. Parodi [55b,55a], E.W.P. Parrish [121], J.A. Parsons [39], U. Parzefall [52], L. Pascual Dominguez [136], V.R. Pascuzzi [167], J.M.P. Pasner [146], E. Pasqualucci [72a], S. Passaggio [55b], F. Pastore [93], P. Pasuwan [45a,45b], S. Pataraia [99], J.R. Pater [100], A. Pathak [181], T. Pauly [36], B. Pearson [115], M. Pedersen [134], L. Pedraza Diaz [119], R. Pedro [140a], T. Peiffer [53], S.V. Peleganchuk [122b,122a], O. Penc [141], H. Peng [60a], B.S. Peralva [80a], M.M. Perego [132], A.P. Pereira Peixoto [140a], D.V. Perepelitsa [29], F. Peri [19], L. Perini [68a,68b], H. Pernegger [36], S. Perrella [69a,69b], K. Peters [46], R.F.Y. Peters [100], B.A. Petersen [36], T.C. Petersen [40], E. Petit [101], A. Petridis [1], C. Petridou [162], P. Petroff [132], M. Petrov [135], F. Petrucci [74a,74b], M. Pettee [183], N.E. Pettersson [102], K. Petukhova [143], A. 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Resseguie [137], S. Rettie [175], E. Reynolds [21], O.L. Rezanova [122b,122a], P. Reznicek [143], E. Ricci [75a,75b], R. Richter [115], S. Richter [46], E. Richter-Was [83b], O. Ricken [24], M. Ridel [136], P. Rieck [115], C.J. Riegel [182], O. Rifki [46], M. Rijssenbeek [155], A. Rimoldi [70a,70b], M. Rimoldi [20], L. Rinaldi [23b], G. Ripellino [154], B. Ristić [89], E. Ritsch [36], I. Riu [14], J.C. Rivera Vergara [147a], F. Rizatdinova [129], E. Rizvi [92], C. Rizzi [36], R.T. Roberts [100], S.H. Robertson [103,ad], M. Robin [46], D. Robinson [32], J.E.M. Robinson [46], A. Robson [57], E. Rocco [99], C. Roda [71a,71b], S. Rodriguez Bosca [174], A. Rodriguez Perez [14], D. Rodriguez Rodriguez [174], A.M. Rodríguez Vera [168b], S. Roe [36], O. Røhne [134], R. Röhrig [115], C.P.A. Roland [65], J. Roloff [59], A. Romaniouk [112], M. Romano [23b,23a], N. Rompotis [90], M. Ronzani [124], L. Roos [136], S. Rosati [72a], K. Rosbach [52], N-A. Rosien [53], G. Rosin [102], B.J. 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Salt [174], D. Salvatore [41b,41a], F. Salvatore [156], A. Salvucci [63a,63b,63c], A. Salzburger [36], J. Samarati [36], D. Sammel [52], D. Sampsonidis [162], D. Sampsonidou [162], J. Sánchez [174], A. Sanchez Pineda [66a,66c], H. Sandaker [134], C.O. Sander [46], I.G. Sanderswood [89], M. Sandhoff [182], C. Sandoval [22], D.P.C. Sankey [144], M. Sannino [55b,55a], Y. Sano [117], A. Sansoni [51], C. Santoni [38], H. Santos [140a,140b], S.N. Santpur [18], A. Santra [174], A. Sapronov [79], J.G. Saraiva [140a,140d], O. Sasaki [81], K. Sato [169], E. Sauvan [5], P. Savard [167,ax], N. Savic [115], R. Sawada [163], C. Sawyer [144], L. Sawyer [95,al], C. Sbarra [23b], A. Sbrizzi [23a], T. Scanlon [94], J. Schaarschmidt [148], P. Schacht [115], B.M. Schachtner [114], D. Schaefer [37], L. Schaefer [137], J. Schaeffer [99], S. Schaepe [36], U. Schäfer [99], A.C. Schaffer [132], D. Schaile [114], R.D. Schamberger [155], N. Scharmberg [100], V.A. Schegelsky [138], D. Scheirich [143], F. 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M. Stankaityte [135], B. Stapf [120], E.A. Starchenko [123], G.H. Stark [146], J. Stark [58], S.H Stark [40], P. Staroba [141], P. Starovoitov [61a], S. Stärz [103], R. Staszewski [84], G. Stavropoulos [44], M. Stegler [46], P. Steinberg [29], A.L. Steinhebel [131], B. Stelzer [152], H.J. Stelzer [139], O. Stelzer-Chilton [168a], H. Stenzel [56], T.J. Stevenson [156], G.A. Stewart [36], M.C. Stockton [36], G. Stoicea [27b], M. Stolarski [140a], P. Stolte [53], S. Stonjek [115], A. Straessner [48], J. Strandberg [154], S. Strandberg [45a,45b], M. Strauss [128], P. Strizenec [28b], R. Ströhmer [177], D.M. Strom [131], R. Stroynowski [42], A. Strubig [50], S.A. Stucci [29], B. Stugu [17], J. Stupak [128], N.A. Styles [46], D. Su [153], S. Suchek [61a], V.V. Sulin [110], M.J. Sullivan [90], D.M.S. Sultan [54], S. Sultansoy [4c], T. Sumida [85], S. Sun [105], X. Sun [3], K. Suruliz [156], C.J.E. Suster [157], M.R. Sutton [156], S. Suzuki [81], M. Svatos [141], M. Swiatlowski [37], S.P. Swift [2], T. Swirski [177], A. Sydorenko [99], I. Sykora [28a], M. Sykora [143], T. Sykora [143], D. Ta [99], K. Tackmann [46,y], J. Taenzer [161], A. Taffard [171], R. Tafirout [168a], E. Tahirovic [92], H. Takai [29], R. Takashima [86], K. Takeda [82], T. Takeshita [150], E.P. Takeva [50], Y. Takubo [81], M. Talby [101], A.A. Talyshev [122b,122a], N.M. Tamir [161], J. Tanaka [163], M. Tanaka [165], R. Tanaka [132], B.B. Tannenwald [126], S. Tapia Araya [173], S. Tapprogge [99], A. Tarek Abouelfadl Mohamed [136], S. Tarem [160], G. Tarna [27b,c], G.F. Tartarelli [68a], P. Tas [143], M. Tasevsky [141], T. Tashiro [85], E. Tassi [41b,41a], A. Tavares Delgado [140a,140b], Y. Tayalati [35e], A.J. Taylor [50], G.N. Taylor [104], W. Taylor [168b], A.S. Tee [89], R. Teixeira De Lima [153], P. Teixeira-Dias [93], H. Ten Kate [36], J.J. Teoh [120], S. Terada [81], K. Terashi [163], J. Terron [98], S. Terzo [14], M. Testa [51], R.J. Teuscher [167,ad], S.J. Thais [183], T. 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Tsiareshka [107,aj], A. Tsirigotis [162], N. Tsirintanis [9], V. Tsiskaridze [155], E.G. Tskhadadze [159a], M. Tsopoulou [162], I.I. Tsukerman [111], V. Tsulaia [18], S. Tsuno [81], D. Tsybychev [155], Y. Tu [63b], A. Tudorache [27b], V. Tudorache [27b], T.T. Tulbure [27a], A.N. Tuna [59], S. Turchikhin [79], D. Turgeman [180], I. Turk Cakir [4b,u], R.J. Turner [21], R.T. Turra [68a], P.M. Tuts [39], S Tzamarias [162], E. Tzovara [99], G. Ucchielli [47], K. Uchida [163], I. Ueda [81], M. Ughetto [45a,45b], F. Ukegawa [169], G. Unal [36], A. Undrus [29], G. Unel [171], F.C. Ungaro [104], Y. Unno [81], K. Uno [163], J. Urban [28b], P. Urquijo [104], G. Usai [8], J. Usui [81], L. Vacavant [101], V. Vacek [142], B. Vachon [103], K.O.H. Vadla [134], A. Vaidya [94], C. Valderanis [114], E. Valdes Santurio [45a,45b], M. Valente [54], S. Valentinetti [23b,23a], A. Valero [174], L. Valéry [46], R.A. Vallance [21], A. Vallier [36], J.A. Valls Ferrer [174], T.R. Van Daalen [14], P. Van Gemmeren [6], I. Van Vulpen [120], M. Vanadia [73a,73b], W. Vandelli [36], A. Vaniachine [166], D. Vannicola [72a,72b], R. Vari [72a], E.W. Varnes [7], C. Varni [55b,55a], T. Varol [42], D. Varouchas [132], K.E. Varvell [157], M.E. Vasile [27b], G.A. Vasquez [176], J.G. Vasquez [183], F. Vazeille [38], D. Vazquez Furelos [14], T. Vazquez Schroeder [36], J. Veatch [53], V. Vecchio [74a,74b], M.J. Veen [120], L.M. Veloce [167], F. Veloso [140a,140c], S. Veneziano [72a], A. Ventura [67a,67b], N. Venturi [36], A. Verbytskyi [115], V. Vercesi [70a], M. Verducci [74a,74b], C.M. Vergel Infante [78], C. Vergis [24], W. Verkerke [120], A.T. Vermeulen [120], J.C. Vermeulen [120], M.C. Vetterli [152,ax], N. Viaux Maira [147b], M. Vicente Barreto Pinto [54], T. Vickey [149], O.E. Vickey Boeriu [149], G.H.A. Viehhauser [135], L. Vigani [135], M. Villa [23b,23a], M. Villaplana Perez [68a,68b], E. Vilucchi [51], M.G. Vincter [34], V.B. Vinogradov [79], A. Vishwakarma [46], C. 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